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(54) **SELF MODE-LOCKING SEMICONDUCTOR DISK LASER**

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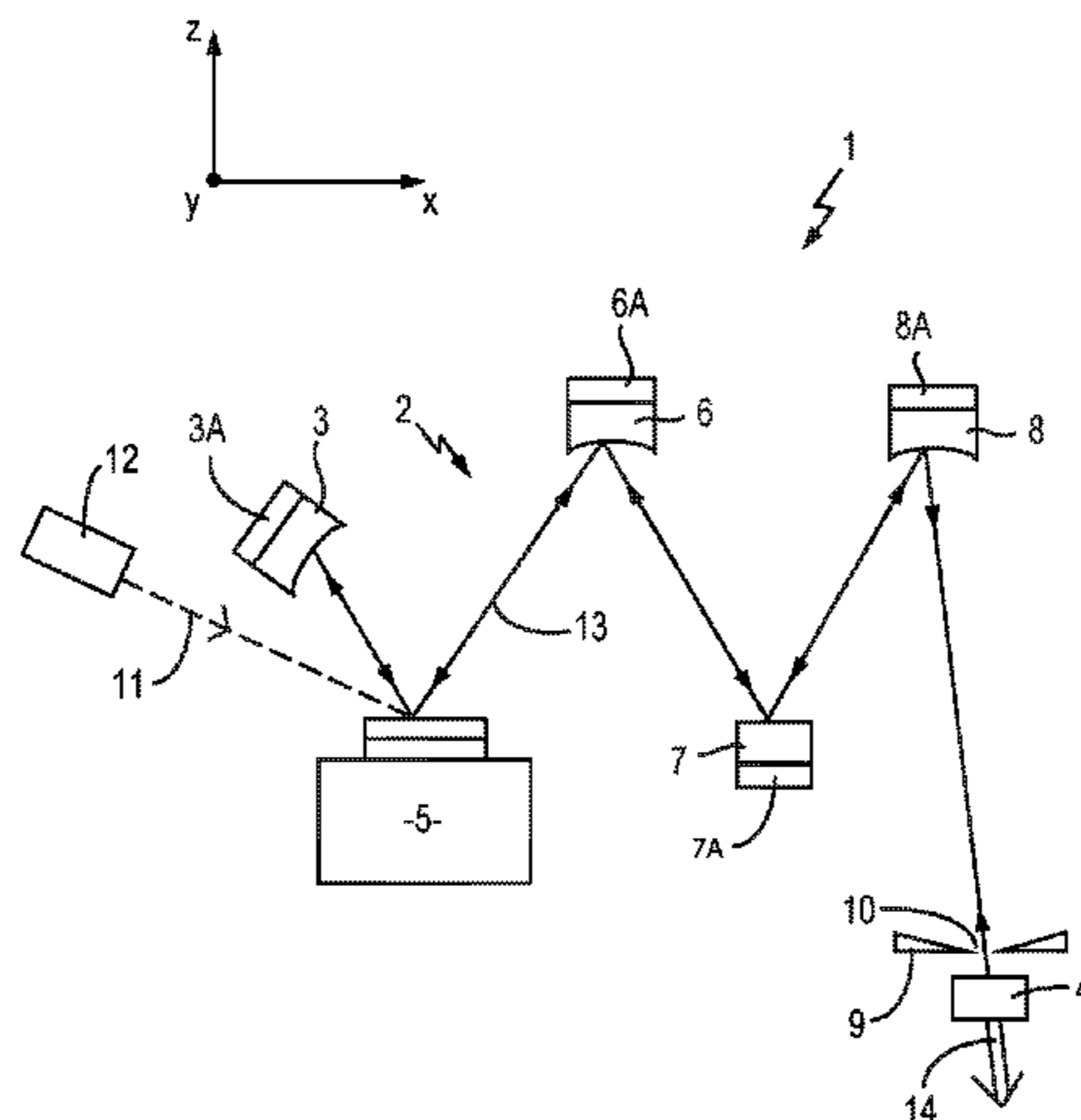
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(57) **ABSTRACT**

The present invention describes a self mode locking laser and a method for self mode locking a laser. The laser (1) comprises a resonator terminated by first (3) and second (4) mirrors and folded by a third mirror (5). The third mirror comprises a single distributed Bragg reflector (17) upon which is mounted a multilayer semiconductor gain medium (18) and which includes at least one quantum well layer and an optical Kerr lensing layer (22). Self mode locking may be achieved by configuring the laser resonator such that the lensing effect of the Kerr lensing layer acts to reduce an astigmatism deliberately introduced to the cavity mode. The self mode locking of the laser may be further enhanced by selecting the length of the resonator such that a round trip time of a cavity mode is matched with an upper-state  
(Continued)



lifetime of one or more semiconductor carriers located within the gain medium.

**29 Claims, 5 Drawing Sheets**

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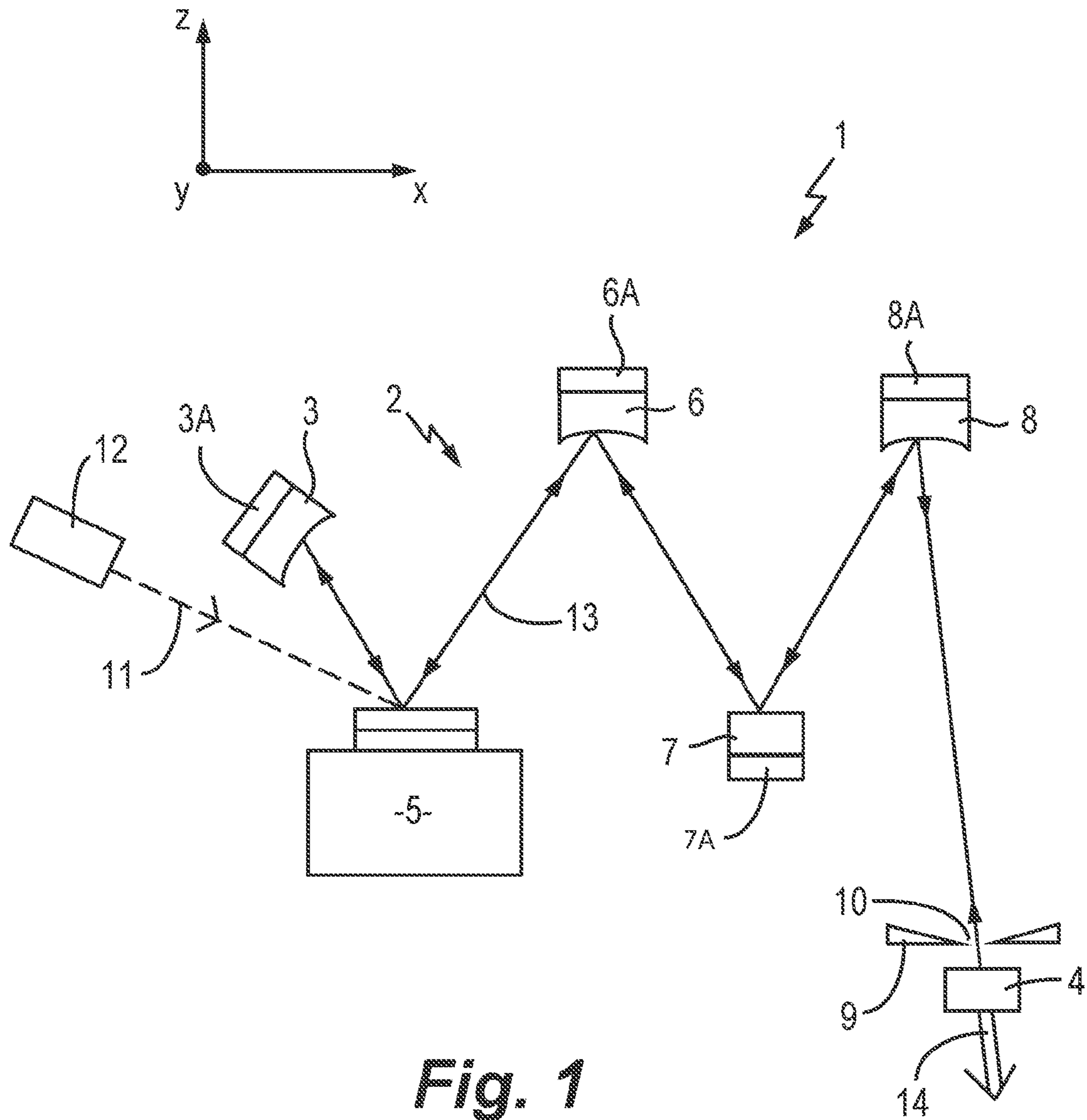
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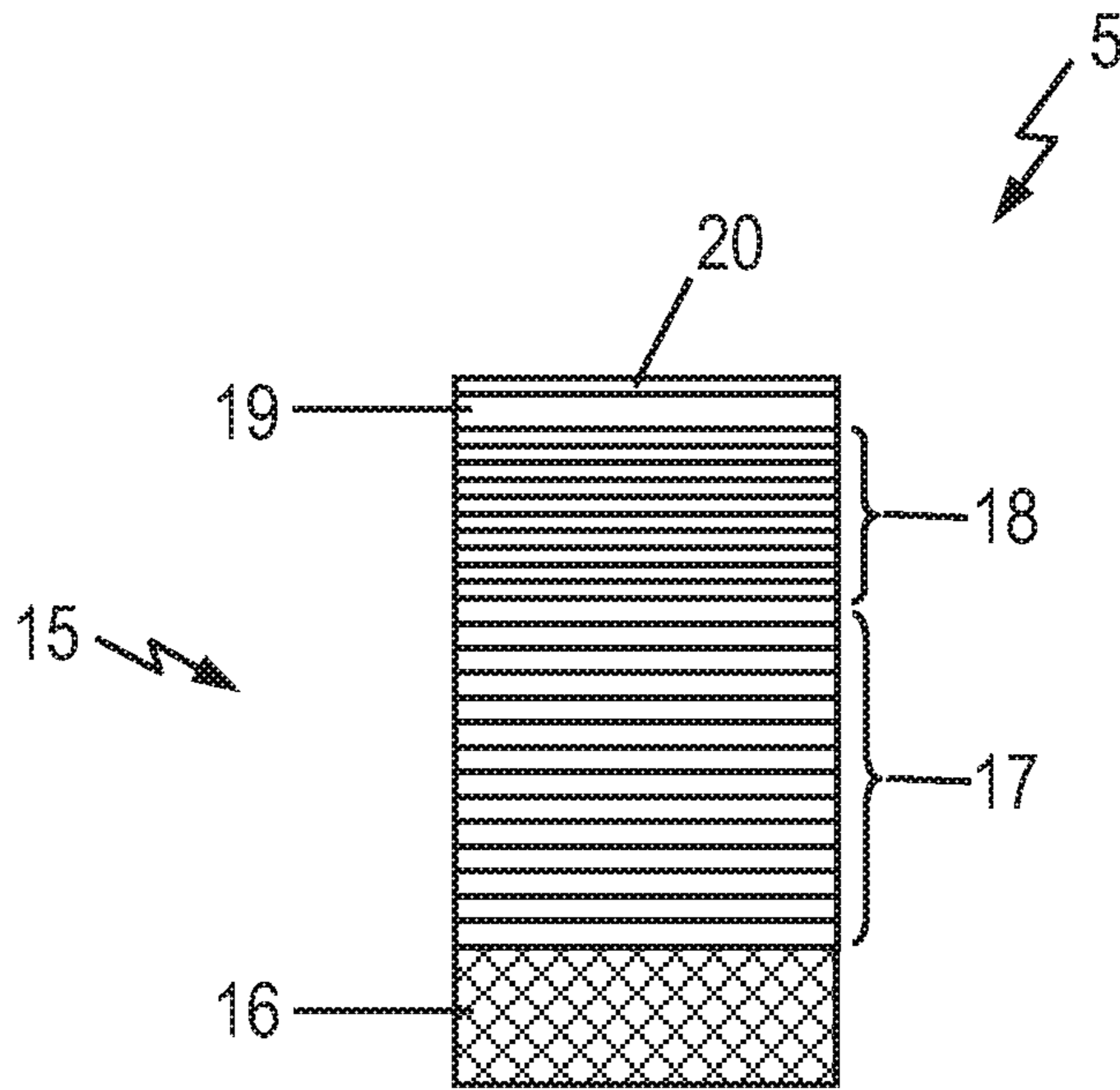
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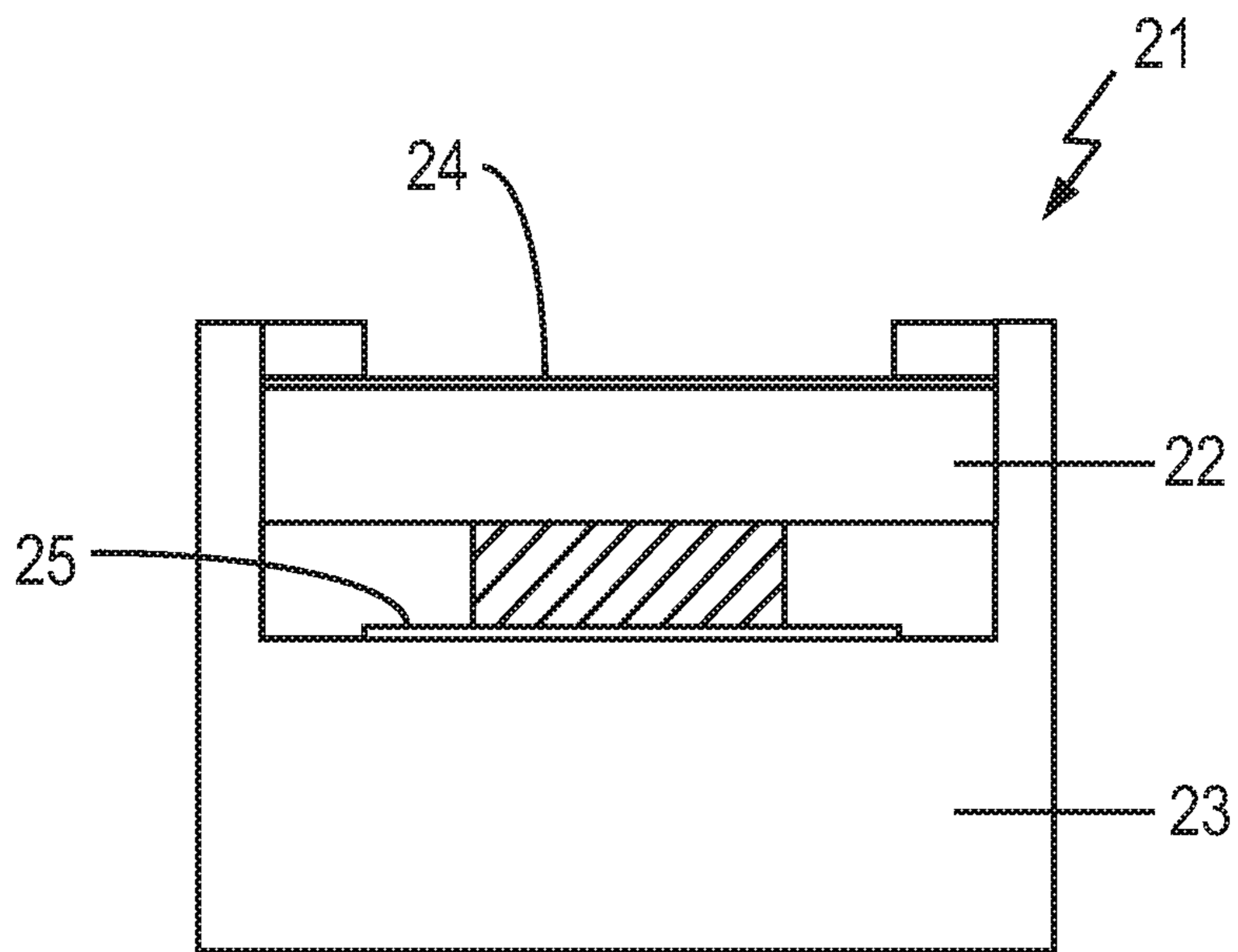
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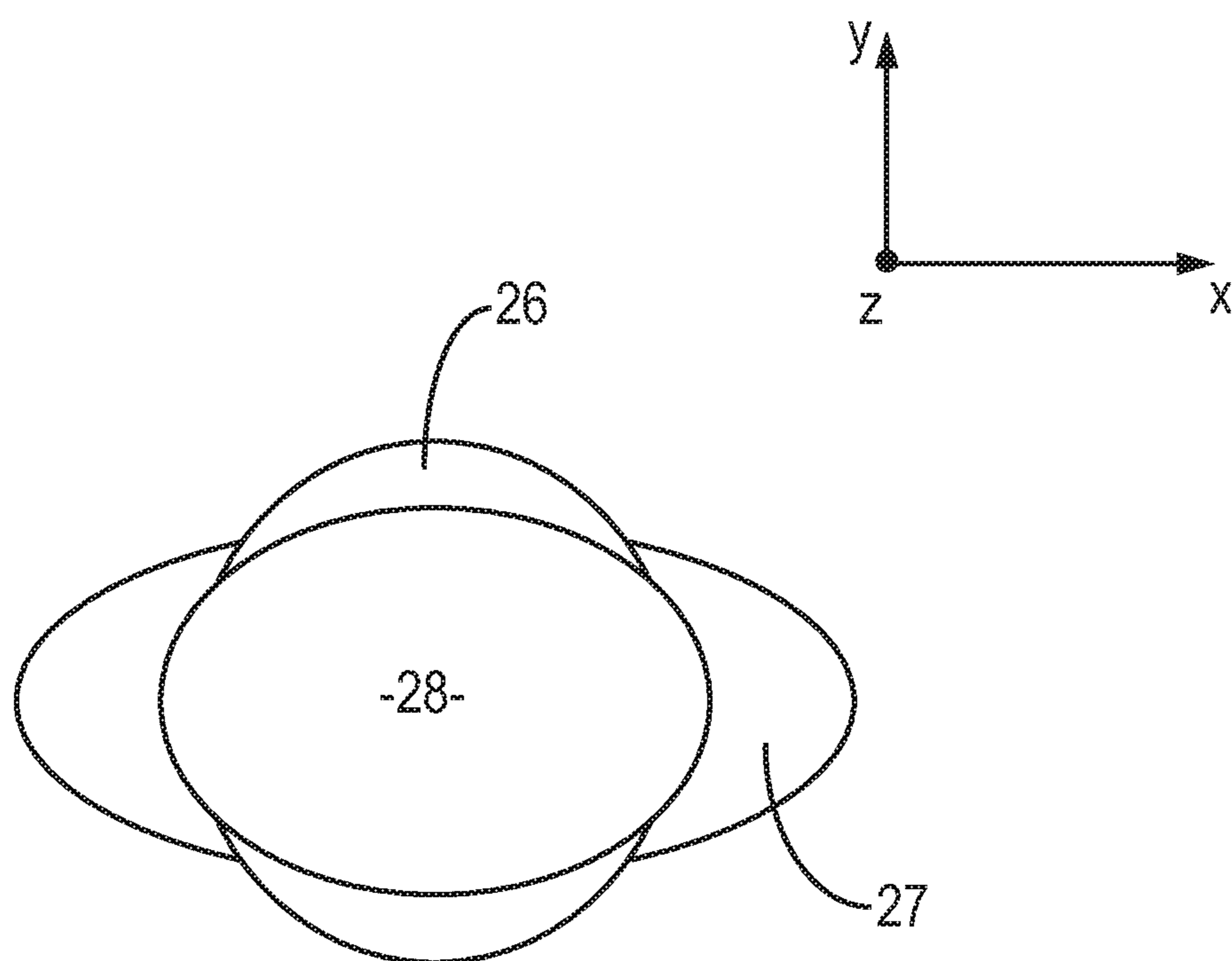




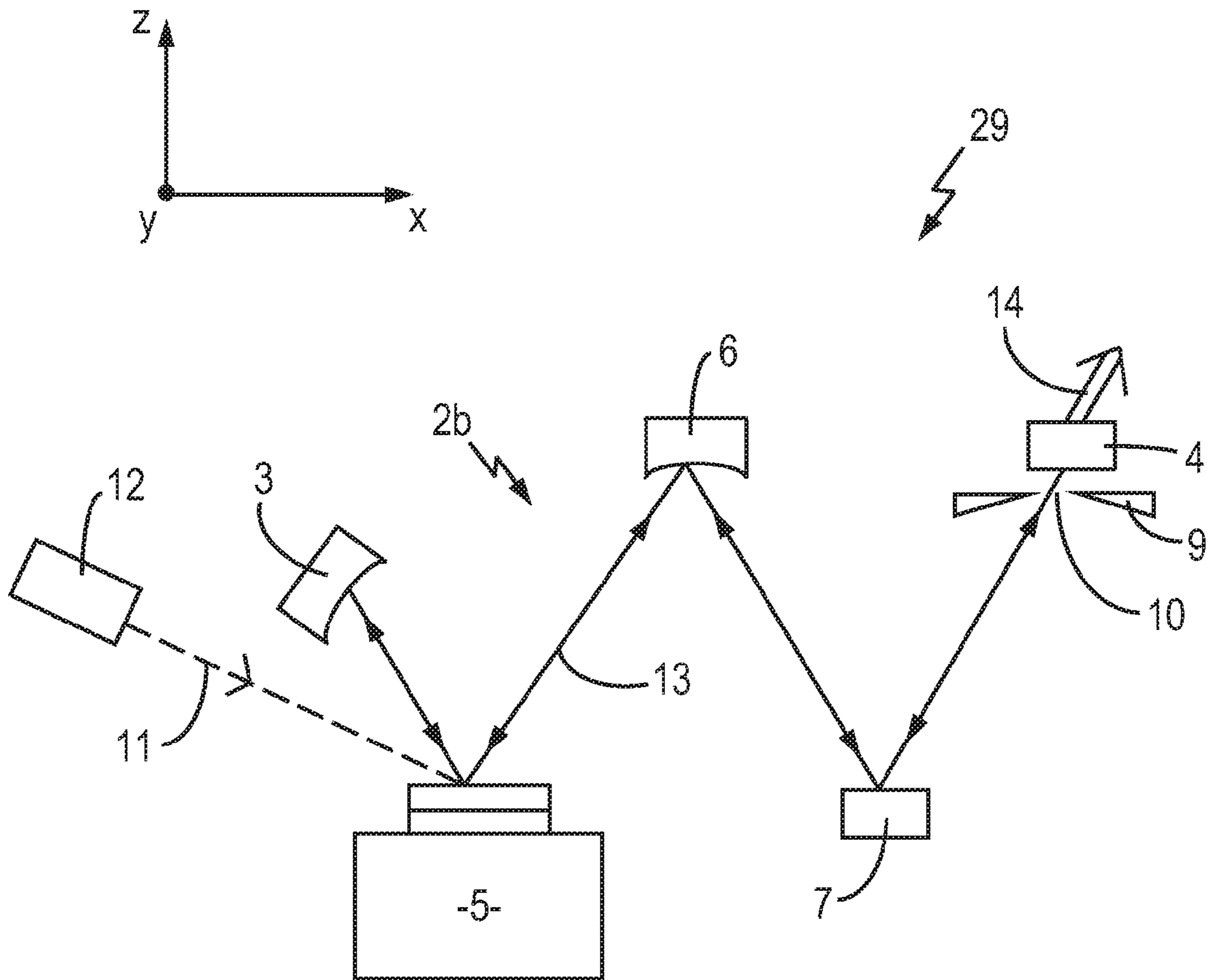
**Fig. 2**



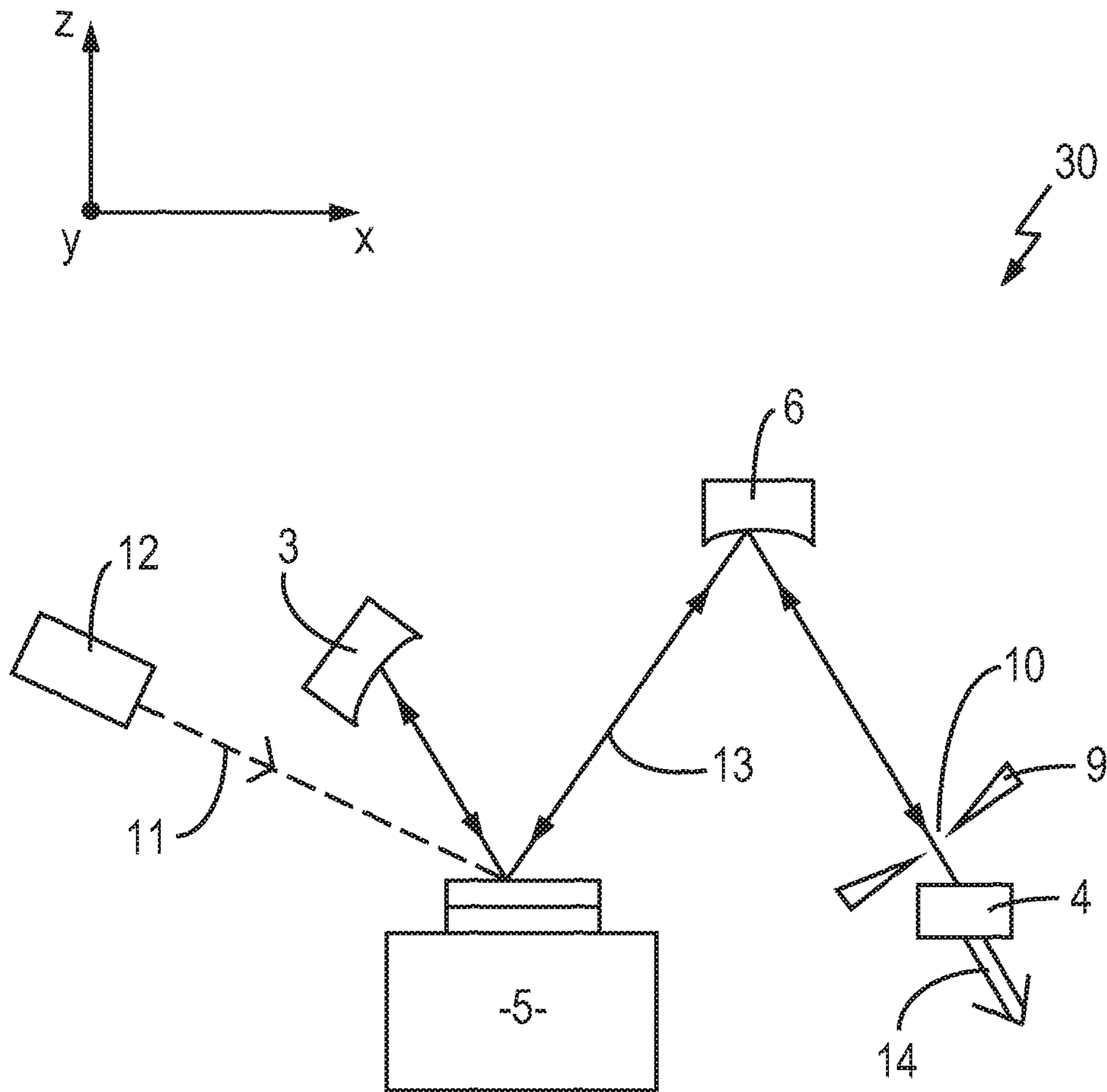
**Fig. 3**



**Fig. 4**



**Fig. 5**



**Fig. 6**

## SELF MODE-LOCKING SEMICONDUCTOR DISK LASER

This application is the U.S. national phase of International Application No. PCT/GB2013/050799 filed 27 Mar. 2013 which designated the U.S. and claims priority to GB 1205587.7 filed 29 Mar. 2012, the entire contents of each of which are hereby incorporated by reference.

The present invention relates to the field of semiconductor lasers and in particular to a semiconductor disc laser (SDL) configured to emit ultra short pulses of radiation.

It is noted that SDLs are also known in the art as Vertical External Cavity Emitting Lasers (VECSELs) or Optically Pumped Semiconductor Lasers (OPSLs). Therefore the term semiconductor disc laser (SDL) when used throughout the present description is used to refer to each of these systems.

The term “ultra short” pulses as used within the following description refers to pulses having a duration from about 100 picoseconds (ps) down to a few femtoseconds (fs).

Ultra short pulses of optical radiation generated by laser sources are employed in a range of scientific, instrumentation and nonlinear optics applications. One particular application for these ultra short pulses is in the field of nonlinear microscopy for example Two-Photon Excited Fluorescence (TPEF) microscopy or other similar multi-photon microscopy techniques. Historically, Ti:sapphire laser sources have been employed to perform these nonlinear microscopy techniques due to the inherent large tunable ranges (700 nm to 1,000 nm) and peak powers available to such gain mediums. A Ti:sapphire laser system is generally optically pumped at wavelength in the green region of the spectrum and therefore these systems are typically pumped with frequency-doubled solid state lasers having a neodymium-doped gain medium such as neodymium-doped YAG (Nd:YAG) or neodymium-doped yttrium orthovanadate (Nd:YVO<sub>4</sub>) wherein radiation having a fundamental wavelength of about 1064 nm is converted into radiation having a wavelength of about 532 nm by frequency-doubling techniques. As a result, the above described solid state ultrafast lasers are relatively complex, bulky, have high maintenance requirements and most significantly are expensive to produce.

As an alternative to Ti:sapphire laser sources, it is known in the art to employ ultrafast semiconductor saturable absorber mirrors (SESAM) for mode locking diode pumped solid state-lasers. Compact designs have been realised by “folding” long cavities or by increasing the repetition rate of the lasers which naturally allows for a shorter cavity length. The main drawback of systems that employ SESAMs is that they are still relatively complex to produce and maintain.

More recently compact ultrafast chromium-doped laser systems such as Cr:LiCAF, Cr:LiSAF, and Cr:LiSGAF lasers have been developed and employed for nonlinear TPEF microscopy. Although average powers of up to 500 mW have been demonstrated, systems based on such materials are often limited in their ability to sufficiently scale their average power.

Other alternative sources based on fibre lasers and semiconductor laser diode with amplification schemes have also been successfully demonstrated as compact lasers for nonlinear microscopy applications. Fibre lasers can be employed to generate very short pulses via passive mode locking techniques. They are however limited to operating at wavelengths around 1030 nm and 1550 nm and the second harmonics produced from these fundamental wavelengths. Within semiconductor lasers with amplification schemes e.g. gain-switched sources based on vertical cavity surfaces emitting lasers (VECSELs); gain switched InGaAsP Dis-

tributed Feedback-Bragg (DFB), laser diode; and external cavity mode-locked laser diode consisting of multiple quantum wells (AlGaAs), the simplicity or compactness of the system is compromised as they all require several stages to compress and or amplify the generated optical pulses.

One key aspect of optimising a compact laser system for nonlinear microscopy applications is the critical trade off between repetition rate of the laser and the multi-photon signal strength generated. The signal strength in TPEF microscopy scales as the product of the peak power times the average power (assuming image spot size, absorption, sample, detection path, etc. remain constant). An example of an ultra short pulse mode-locked SDL is described in US patent publication number US 2009/0290606. This document describes optically pumping the SDL gain structure with optical pulses, delivered at a pulse repetition frequency corresponding to a resonant frequency of the laser resonator. The resonator additionally includes a passive mode locking arrangement such as an optical element that exhibits a strong optical Kerr effect, a second harmonic generating nonlinear crystal which acts in conjunction with the output coupler, or an output coupler which comprises a semiconductor saturable absorber mirror (SESAM). Although the described combination of optically pumping the gain structure with an optical pump pulse source in conjunction with a passive mode locking scheme is capable of generating pulses ranging from 100 ps to ~100 fs, the incorporation of such elements adds to the overall complexity and expense of the ultra short pulse source.

It is therefore an object of an embodiment of the present invention to obviate or at least mitigate the foregoing disadvantages of the ultra short pulse sources of radiation known in the art.

It is a further object of an embodiment of the present invention to provide a self-mode locking semiconductor disc laser system.

### SUMMARY OF INVENTION

According to a first aspect of the present invention there is provided a self mode locking laser the laser comprising a resonator terminated by first and second mirrors and folded by a third mirror, the third mirror surmounted by a multi-layer semiconductor gain medium including at least one quantum well layer and an optical Kerr lensing layer, wherein a length of the resonator is selected such that a round trip time of a cavity mode corresponds with an upper-state lifetime of one or more semiconductor carriers located within the gain medium.

The above configuration provides a laser which mode locks without requiring a dedicated passive or active mode locking elements to be incorporated therein. By selecting the length of the resonator to be comparable with an upper-state lifetime of one or more semiconductor carriers located within the gain medium causes a small perturbation on the intensity of the output field of the laser which is sufficient for the optical Kerr lensing layer to induce mode locking on the output field. This results in a semiconductor laser that is simpler to operate and maintain and which has reduced production costs compared with those systems known in the art.

The second mirror may be partially reflective and partially transmissive at a fundamental wavelength of the gain medium so as to act as an output coupler for the resonator.



Most preferably the optical Kerr lensing layer comprises a heat spreader mounted upon the semiconductor gain medium. The heat spreader may comprise a layer of diamond crystal.

The resonator may further comprise an aperture stop having an aperture located therein. Preferably the aperture stop is located adjacent to the second mirror. Alternatively the aperture is located adjacent to the first mirror.

The resonator may be additionally folded by a fourth mirror, the fourth mirror being located between the second and third mirrors. The fourth mirror preferably has a concave radius of curvature.

The resonator may be additionally folded by a fifth mirror, the fifth mirror being located between the second and fourth mirrors. The fifth mirror is preferably planar.

The resonator may be additionally folded by a sixth mirror, the sixth mirror being located between the second and fifth mirrors. The sixth mirror preferably has a concave radius of curvature.

Optionally the laser comprises a continuous wave (cw) optical field source the output from which is configured to pump the gain medium. The (cw) optical field source may comprise a fibre coupled laser diode system

The resonator may further comprise an astigmatism controller that provides a means for introducing astigmatism to the cavity mode at the gain medium.

In this embodiment the resonator is preferably configured such that the Kerr lensing layer acts to compensate for the astigmatism introduced to the cavity mode. By compensating for the astigmatism introduced to the cavity mode the area of overlap between the cavity mode and a pump spot at the gain medium is increased. As a result the self mode locking nature of the laser is enhanced.

The astigmatism controller may comprise a mirror rotating means. The mirror rotating means may be employed to rotate the fourth mirror so as to vary the angle of incidence of a resonating field upon the fourth mirror.

Most preferably the laser provides an output field comprising ultra short pulses. The ultra short pulses may have a pulse width in the range of 100 ps to 100 fs.

According to a second aspect of the present invention there is provided a method of self mode locking a laser the method comprising

- providing a resonator terminated by first and second mirrors and folded by a third mirror, the third mirror surmounted by a multilayer semiconductor gain medium including at least one quantum well layer and an optical Kerr lensing layer; and
- selecting a length of the resonator such that a round trip time of a cavity mode corresponds with an upper-state lifetime of one or more semiconductor carriers located within the gain medium.

The method of self mode locking a laser may further comprise locating an aperture stop having an aperture located within the resonator.

Preferably the aperture stop is located adjacent to the second mirror. Alternatively the aperture is located adjacent to the first mirror.

The method of self mode locking a laser may further comprise folding the cavity by providing a fourth mirror between the second and third mirrors.

The method of self mode locking a laser may further comprise folding the cavity by providing a fifth mirror between the second and fourth mirrors.

The method of self mode locking a laser may further comprise folding the cavity by providing a sixth mirror between the second and fifth mirrors.

The method of self mode locking a laser may further comprise providing a continuous wave (cw) optical field configured to pump the gain medium.

The method of self mode locking a laser may further comprise introducing astigmatism to the cavity mode at the gain medium.

The astigmatism may be introduced to the cavity mode by rotating the fourth mirror so as to increase the angle of incidence of a resonating field upon the fourth mirror.

The method of self mode locking a laser may further comprise configuring the resonator such that the Kerr lensing layer acts to compensate for the astigmatism introduced to the cavity mode. In this way an area of overlap between the cavity mode and a pump spot at the gain medium is increased.

Embodiments of the second aspect of the invention may comprise features to implement the preferred or optional features of the first aspect of the invention or vice versa.

According to a third aspect of the present invention there is provided a self mode locking laser the laser comprising a resonator terminated by first and second mirrors and folded by a third mirror, the third mirror surmounted by a multilayer semiconductor gain medium including at least one quantum well layer and an optical Kerr lensing layer, a continuous wave (cw) optical field source the output from which is configured to pump the gain medium, wherein a length of the resonator is selected such that a round trip time of a cavity mode corresponds with an upper-state lifetime of one or more semiconductor carriers located within the gain medium.

Embodiments of the third aspect of the invention may comprise features to implement the preferred or optional features of the first or second aspects of the invention or vice versa.

According to a fourth aspect of the present invention there is provided a method of self mode locking a laser the method comprising

- providing a resonator terminated by first and second mirrors and folded by a third mirror, the third mirror surmounted by a multilayer semiconductor gain medium including at least one quantum well layer and an optical Kerr lensing layer;
- providing a continuous wave (cw) optical field configured to pump the gain medium; and
- selecting a length of the resonator such that a round trip time of a cavity mode corresponds with an upper-state lifetime of one or more semiconductor carriers located within the gain medium.

Embodiments of the fourth aspect of the invention may comprise features to implement the preferred or optional features of the first to third aspects of the invention or vice versa.

According to a fifth aspect of the present invention there is provided a self mode locking laser the laser comprising a resonator terminated by first and second mirrors and folded by a third mirror, the third mirror surmounted by a multilayer semiconductor gain medium including at least one quantum well layer and an optical Kerr lensing layer, an astigmatism controller that provides a means for introducing astigmatism to a cavity mode at the gain medium, wherein the resonator is configured such that the Kerr lensing layer acts to compensate for the astigmatism introduced to the cavity mode.

By configuring the resonator such that the Kerr lensing layer acts to compensate for the astigmatism introduced to the cavity mode the area of overlap between the cavity mode and a pump spot at the gain medium is increased. As a result

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the above configuration provides a laser which mode locks without requiring a dedicated passive or active mode locking elements to be incorporated therein. This results in a semiconductor laser that is simpler to operate and maintain and which has reduced production costs compared with those systems known in the art.

The second mirror may be partially reflective and partially transmissive at a fundamental wavelength of the gain medium so as to act as an output coupler for the resonator.

Most preferably the optical Kerr lensing layer comprises a heat spreader mounted upon the semiconductor gain medium. The heat spreader may comprise a layer of diamond crystal.

The resonator may further comprise an aperture stop having an aperture located therein. Preferably the aperture stop is located adjacent to the second mirror. Alternatively the aperture is located adjacent to the first mirror.

The resonator may be additionally folded by a fourth mirror, the fourth mirror being located between the second and third mirrors. The fourth mirror preferably has a concave radius of curvature.

The resonator may be additionally folded by a fifth mirror, the fifth mirror being located between the second and fourth mirrors. The fifth mirror is preferably planar.

The resonator may be additionally folded by a sixth mirror, the sixth mirror being located between the second and fifth mirrors. The sixth mirror preferably has a concave radius of curvature.

Optionally the laser comprises a continuous wave (cw) optical field source the output from which is configured to pump the gain medium. The (cw) optical field source may comprise a fibre coupled laser diode system

The astigmatism controller may comprise a mirror rotating means.

The mirror rotating means may be employed for rotating the fourth mirror so as to vary the angle of incidence of a resonating field upon the fourth mirror.

The length of the resonator may be selected such that a round trip time of a cavity mode corresponds with an upper-state lifetime of one or more semiconductor carriers located within the gain medium.

Most preferably the laser provides an output field comprising ultra short pulses. The ultra short pulses may have a pulse width in the range of 100 ps to 100 fs.

Embodiments of the fifth aspect of the invention may comprise features to implement the preferred or optional features of the first to fourth aspects of the invention or vice versa.

According to a sixth aspect of the present invention there is provided a method of self mode locking a laser the method comprising

- providing a resonator terminated by first and second mirrors and folded by a third mirror, the third mirror surmounted by a multilayer semiconductor gain medium including at least one quantum well layer and an optical Kerr lensing layer;
- introducing astigmatism to the cavity mode at the gain medium; and
- configuring the resonator such that the Kerr lensing layer acts to compensate for the astigmatism introduced to the cavity mode.

The method of self mode locking a laser may further comprise locating an aperture stop having an aperture located within the resonator.

Preferably the aperture stop is located adjacent to the second mirror. Alternatively the aperture is located adjacent to the first mirror.

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The method of self mode locking a laser may further comprise folding the cavity by providing a fourth mirror between the second and third mirrors.

The astigmatism may be introduced to the cavity mode by rotating the fourth mirror so as to increase the angle of incidence of a resonating field upon the fourth mirror.

The method of self mode locking a laser may further comprise folding the cavity by providing a fifth mirror between the second and fourth mirrors.

The method of self mode locking a laser may further comprise folding the cavity by providing a sixth mirror between the second and fifth mirrors.

The method of self mode locking a laser may further comprise providing a continuous wave (cw) optical field configured to pump the gain medium.

The method of self mode locking a laser may further comprise selecting a length of the resonator such that a round trip time of a cavity mode corresponds with an upper-state lifetime of one or more semiconductor carriers located within the gain medium.

Embodiments of the sixth aspect of the invention may comprise features to implement the preferred or optional features of the first to fifth aspects of the invention or vice versa.

## BRIEF DESCRIPTION OF DRAWINGS

Aspects and advantages of the present invention will become apparent upon reading the following detailed description and upon reference to the following drawings in which:

FIG. 1 presents a schematic representation of a self mode-locking, external-cavity surface-emitting, semiconductor laser in accordance with an embodiment of the present invention;

FIG. 2 presents a schematic representation of a semiconductor disk laser (SDL) employed by the laser of FIG. 1;

FIG. 3 present a schematic representation of a cooling apparatus employed in conjunction with the SDL of FIG. 2;

FIG. 4 presents a schematic representation of a cavity mode, a pump spot and a Kerr Lens mode at the surface of the SDL of FIG. 1;

FIG. 5 presents a semiconductor laser in accordance with an alternative embodiment of the present invention; and

FIG. 6 presents a semiconductor laser in accordance with a further alternative embodiment of the present invention.

In the description which follows, like parts are marked throughout the specification and drawings with the same reference numerals. The drawings are not necessarily to scale and the proportions of certain parts have been exaggerated to better illustrate details and features of embodiments of the invention.

## DETAILED DESCRIPTION

Referring initially to FIG. 1, a schematic representation of a self mode-locking, external-cavity surface-emitting, semiconductor laser 1 in accordance with an embodiment of the present invention is shown. For clarity of understanding axes are provided within this figure. The plane of the cavity referred to below is the plane defined by the x and z axes.

The self mode-locking laser 1 can be seen to comprise a laser-resonator 2 formed between a first 3 and a second mirror 4 and includes a multilayer, optically-pumped, semiconductor disk laser (SDL) 5 further details of which are provided below with reference to FIGS. 2 and 3. As can be seen the SDL 5 is arranged to function as a first folding

mirror for the resonator **2**. Three further folding mirrors **6**, **7** and **8** are included within the resonator **2** and so the resonator **2** can be considered to be a four times folded resonator.

The first mirror **3** and the three folding mirrors **6**, **7** and **8** are arranged to be highly reflective at the fundamental wavelength of the SDL **5** while the second mirror **4** is partially reflective and partially transmissive at this fundamental wavelength and so acts as an output coupler for the resonator **2**. An aperture stop **9** comprising an aperture **10**, such as a slit aperture, may be located adjacent to the second mirror **4**. The aperture may be orientated in the plane of the cavity, in a plane perpendicular to the plane of the cavity or indeed comprise an iris and thus have a component in both planes.

The mirrors **3**, **6**, **7** and **8** may be mounted within corresponding piezo-electric controlled mirror mounts **3A**, **6A**, **7A**, **8A** so as to provide a means for fine adjusting the alignment of these components. Furthermore, mirrors **3**, **6** and **8** are concave mirrors while the mirrors **4** and **7** and the SDL **5** are substantially planar reflecting elements such that the resonator **2** is optically stable and the shape of the cavity mode at the SDL **5** can be controlled, as discussed in further detail below.

A continuous wave (cw) optical pumping field **11** suitable for pumping the SDL **5** is provided by employing a fibre coupled laser diode system **12**. In the presently described embodiment the fibre coupled laser diode system **12** is configured to generate a cw optical pumping field **11** at 808 nm. A DILAS® M1F4S22-808 30C-SS2.1 is an example of one such suitable fibre coupled laser diode system **12**.

In the presently described embodiment the fibre coupled laser diode system **12** is arranged to pump the gain medium **18** at an angle suitable for providing an elliptical pump spot at the surface of the gain medium **18**. It will be appreciated by the skilled reader that the present invention is not so limited and that the fibre coupled laser diode system **12** could provide a pump field **11** that is perpendicular to the gain medium **18** so as to provide a circular pump spot at the surface of the gain medium **18**. The fibre coupled laser diode system **12** may also be arranged to pump the gain medium **18** by pumping through the first mirror **3**.

In FIG. **1** the intra cavity resonating field is depicted generally by reference numeral **13** while the ultra short pulsed output field from the laser resonator **2** is depicted generally by reference numeral **14**.

A schematic representation of the SDL **5** is presented in FIG. **2**. The SDL **5** can be seen to comprise a wafer structure **15** that is grown by a metal-organic chemical vapour deposition (MOCVD) technique on a GaAs substrate **16**. The deposition of the wafer structure may be achieved by alternative techniques known in the art e.g. molecular beam epitaxy (MBE) deposition techniques. The wafer structure **15** comprises a single distributed Bragg reflector (DBR) region **17**, a gain medium **18**, a carrier confinement potential barrier **19** and an oxidation prevention layer **20**.

There are many variations of the wafer structures **15** incorporated within the SDLs known to those skilled in the art and the present invention is not limited to use with any particular DBR region **17** or gain medium **18** structure. In general, the gain medium **18** will comprise multiple quantum wells equally spaced between half-wave structures that allow the SDL **5** to be optically pumped at a convenient pump wavelength while the DBR regions **17** generally comprise multiple pairs of quarter-wave layers that exhibit high reflectivities.

The presently described embodiments comprise a gain medium **18** comprising InGaAs quantum wells equally spaced between half-wave GaAs structures that allow the SDL **5** to be optically pumped at 808 nm while generating an output at 980 nm. The DBR regions **17** comprise thirty pairs of AlAs—GaAs quarter-wave layers that produce reflectivities greater than 99.9% centred at 980 nm while the carrier confinement potential barrier **19** comprises a single wavelength-thick Al<sub>0.3</sub>Ga<sub>0.7</sub>As layer. The oxidation prevention layer **20** may comprise a thin GaAs cap.

Alternative gain mediums known to those skilled in the art that may alternatively be used include alternative gallium arsenide (GaAs) structures capable of generating output wavelengths between 670 nm and 1300 nm; Indium Phosphide (InP) structures capable of generating output wavelengths between 1350 nm and 1600 nm; and Gallium Antimonide (GaSb) structures capable of generating output wavelengths between 1800 nm and 2700 nm. These gain mediums may be based on quantum wells or quantum dots as known to those skilled in the art.

For reasons as will be described in further detail below, the length of the resonator **2** may be selected such that the round trip time of the cavity mode corresponds to the upper-state lifetime of the semiconductor carriers located within the gain medium **18**. In the presently described embodiment the lifetime of the semiconductor carriers is around 5 ns, giving the resonator a length of around 750 nm and a repetition rate of around 200 MHz.

This arrangement is counter intuitive to the teachings within the art where it is generally desirable to make the length of a resonator as small as possible so as assist in the overall miniaturisation of the system. The main restrictions on the minimum length of a resonator is the requirement to provide sufficient physical space for all of the optical components required to be incorporated into the system and to allow for the desired cavity mode characteristics to be achieved. In systems known in the art the selected resonator lengths result in a round trip time for the cavity mode that is much lower than the upper-state lifetime of the associated gain medium, normally by several orders of magnitude.

FIG. **3** presents further detail of a cooling apparatus **21** employed in order to improve the operating characteristics of the SDL **5**. In particular, the cooling apparatus **21** comprises a heat spreader **22** and a standard thermoelectric or water cooler **23**. The heat spreader **22** comprises a single diamond crystal that comprises an external, wedged face **24**.

A high performance anti-reflection coating may be deposited on the surface of the wedged face **24**.

The single diamond crystal heat spreader **22** is bonded by optical contacting with the wafer structure **15** so that the gain medium **18** is located between the heat spreader **22** and the DBR region **17**. The wafer structure **15** and heat spreader **22** are then fixed on top of a layer of indium foil **25** onto the thermoelectric or water cooler **23**.

Single diamond crystal is well suited to be employed as the heat spreader **22** since it exhibits comparable thermal conductivity levels as sapphire and silicon carbide. Thus, the described arrangement allows the heat spreader **22** to immediately spread the heat generated within the gain medium **18** by the pump field **11** to the cooling apparatus **21** after it has propagated only a limited distance into the gain medium **18**. As a result the overall efficiency of the SDL **5** is significantly increased.

In addition there is a further inherent advantage of employing the single diamond crystal as the heat spreader **22**. This resides in the fact that the single diamond crystal is a material that exhibits an inherent optical Kerr effect. It is

this effect that is exploited in order to configure the semiconductor laser **1** so as to operate as a self mode locking system, as will now be described in further detail with reference to FIG. **4**.

In particular, FIG. **4** presents a schematic representation of a cavity mode **26**, a pump spot **27** and a Kerr Lens mode **28** at the surface of the SDL **5** of FIG. **1**. The laser is configured such there is an overlap of the area of the cavity mode **26**, the pump spot **27** and the Kerr Lens mode **28** at the surface of the SDL **5**.

The area of the Kerr lens mode **28** at the SDL **5** is defined by the single diamond crystal heat spreader **22** and in the presently described embodiment it exhibits an elliptical profile with its major axis orientated along the x-axis. In a similar manner the pump spot **27** at the SDL **5** is configured to have an elliptical profile with its major axis also orientated along the x-axis. The major axis of the Kerr lens mode **28** in the presently described embodiment is smaller than the major axis of the pump spot **27**.

The concave folding mirror **6** is arranged so as to introduce astigmatism to the cavity mode **26**. This is achieved by rotating the concave folding mirror **6** about the y-axis so as to increase the angle of incidence of the resonating field **13** upon this mirror **6**. As can be seen from FIG. **4**, this rotation results in the cavity mode **26** at the SDL **5** having an elliptical profile with its major axis orientated along the y-axis.

In this configuration the semiconductor laser **1** begins to lase when the gain medium **18** is pumped by the pumping field **11** and the output field **14** is thus generated. Most significant is that the laser is self mode locking such an ultra short output field at 980 nm is produced i.e. pulse widths from 100 ps down to a few femtoseconds can be generated. This result is highly repeatable and the mode locking takes place without any requirement for further input from the operator of the laser **1**.

The inventors believe that there exist two independent mechanisms which contribute to allow for self mode locking of the laser **1**. In the presently described laser **1** these mechanisms are acting in combination but they may alternatively be independently exploited.

The first mechanism for the self mode locking of the laser **1** results from the fact that length of the resonator **2** is selected such that the round trip time of the cavity mode **26** is close to the upper-state lifetime of the semiconductor carriers located within the gain medium **18**. This introduces a small perturbation on the intensity of the output field **14** which is sufficient for the small inherent optical Kerr effect of the single diamond crystal heat spreader **22** to induce mode locking on the output field **14**.

This process is further assisted by the second mechanism which resides in the introduction of the astigmatism to the cavity mode **26** at the surface of the SDL **5**. Once the Kerr lensing effect of the heat spreader **22** commences the major axis of the cavity mode **26** is effectively reduced thus causing a greater overlap between the area of the cavity mode **26** and the pump spot **27**. Thus, by employing the Kerr lensing effect of the heat spreader **22** to overcome an induced astigmatism a second means for self mode locking of the output field **14** is provided.

As will be appreciated by the skilled reader both of these mechanisms may be assisted by the presence of the aperture stop **9** when the aperture **10** is configured such that the lasing mode of the resonator at the aperture **10** is clipped and lasing is not possible in the absence of the Kerr effect induced by

the heat spreader **22**. It will be further appreciated that the aperture stop **9** could alternatively be located adjacent to the first mirror **3**.

FIG. **5** presents a schematic representation of a self mode-locking, external-cavity surface-emitting, semiconductor laser **29** in accordance with an alternative embodiment of the present invention, similar to the laser **1** presented in FIG. **1**. In this embodiment folding mirrors **8** has been replaced by the output coupler **4** such that the resonator **2b** can now be considered to be a three times folded resonator.

FIG. **6** presents a schematic representation of a self mode-locking, external-cavity surface-emitting, semiconductor laser **30** in accordance with a further alternative embodiment of the present invention, similar to the laser **1** presented in FIG. **1**. In this embodiment folding mirrors **8** has been omitted and folding mirror **7** has been replaced by the output coupler **4** such that the resonator **2c** can now be considered to be a two times folded resonator.

It will be appreciated that a number of alternatives may be incorporated into the above described embodiments. For example the structure of the SDL **5** may be varied so as to provide alternative output wavelengths as required by the particular application for which the semiconductor laser is to be employed.

Furthermore, the orientations of the cavity mode **26**, the pump spot **27** and the Kerr Lens mode **28** may be varied such that the angles between the associated major axes vary from the particular described embodiment. What is important is that the resonator is configured such that an astigmatism introduced to the cavity mode **26** by the configuration of the resonator **2** is reduced by the optical Kerr effect induced by the heat spreader **22** when the gain medium **18** is pumped by the pumping field **11** such that the overlap area between the cavity mode **26** and the pump spot **27** is increased.

The heat spreader may alternatively comprise materials other than single diamond crystal as long as the material employed exhibits the required heat spreading and optical Kerr lensing properties. Sapphire ( $\text{Al}_2\text{O}_3$ ) and silicon carbide (SiC) are examples of alternative materials that may be employed to produce the heat spreader.

The described semiconductor lasers offer a number of advantages over those known in the art. When compared to the previously described solid state ultrafast lasers the presently described systems are significantly less complex, more compact, have reduced maintenance requirements and are significantly less expensive to produce.

The fact that the described semiconductor lasers are self mode locking also removes the requirement for dedicated passive or active mode locking elements to be incorporated. This again results in the presently described semiconductor lasers having a reduced complexity, maintenance requirement and associated production costs.

The presently described semiconductor laser systems can be employed to generate pulses having a pulse widths ranging from 100 ps to ~100 fs, at wavelengths between 670 nm and 2700 nm and with power outputs ranging from 100 mW to 5 W.

The above factors make the described semiconductor lasers ideal for use within nonlinear microscopy techniques e.g. Two-Photon Excited Fluorescence (TPEF) microscopy or other similar multi-photon microscopy techniques. For example the short pulse widths allow for significant depth profiling to be performed on Green Fluorescent Proteins (GFPs) which exhibit excitation peaks at 395 nm and 475 nm or 496 nm depending on the particular GFP employed.

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The present invention describes a self mode locking laser and a method for self mode locking a laser. The laser comprises a resonator terminated by first and second mirrors and folded by a third mirror. The third mirror comprises a single distributed Bragg reflector (DBR) upon which is mounted a multilayer semiconductor gain medium and which includes at least one quantum well layer and an optical Kerr lensing layer. Self mode locking may be achieved by selecting the length of the resonator such that a round trip time of a cavity mode is matched with an upper-state lifetime of one or more semiconductor carriers located within the gain medium. The self mode locking of the laser may be further enhanced by configuring the laser resonator such that the lensing effect of the Kerr lensing layer acts to reduce an astigmatism deliberately introduced to the cavity mode.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. The described embodiments were chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. Therefore, further modifications or improvements may be incorporated without departing from the scope of the invention as defined by the appended claims.

The invention claimed is:

1. A self mode locking laser the laser comprising: a resonator terminated by first and second mirrors and folded by a third mirror, the third mirror surmounted by a multilayer semiconductor gain medium including at least one quantum well layer and an optical Kerr lensing layer, wherein a length of the resonator is selected such that a round trip time of a cavity mode is substantially equal to an upper-state lifetime of one or more semiconductor carriers located within the gain medium to introduce a perturbation on an intensity of an output field of the laser causing the optical Kerr lensing layer to induce mode locking on the output field without the use of a saturable absorber.
2. A self mode locking laser as claimed in claim 1 wherein the second mirror is partially reflective and partially transmissive at a fundamental wavelength of the gain medium so as to act as an output coupler for the resonator.
3. A self mode locking laser as claimed in claim 1 wherein the optical Kerr lensing layer comprises a heat spreader mounted upon the semiconductor gain medium.
4. A self mode locking laser as claimed in claim 3 wherein the heat spreader comprises a layer of diamond crystal.
5. A self mode locking laser as claimed in claim 1 wherein the resonator further comprises an aperture stop having an aperture located therein.
6. A self mode locking laser as claimed in claim 5 wherein the aperture stop is located adjacent to the second mirror.
7. A self mode locking laser as claimed in claim 1 wherein the resonator is additionally folded by a fourth mirror, the fourth mirror being located along an optical path between the second and third mirrors.
8. A self mode locking laser as claimed in claim 7 wherein the fourth mirror has a concave radius of curvature.
9. A self mode locking laser as claimed in claim 7 wherein the resonator is additionally folded by a fifth mirror, the fifth mirror being located along an optical path between the second and fourth mirrors.

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10. A self mode locking laser as claimed in claim 9 wherein the fifth mirror is planar.

11. A self mode locking laser as claimed in claim 9 wherein the resonator is additionally folded by a sixth mirror, the sixth mirror being located along an optical path between the second and fifth mirrors.

12. A self mode locking laser as claimed in claim 11 wherein the sixth mirror has a concave radius of curvature.

13. A self mode locking laser as claimed in claim 1 wherein the laser further comprises a continuous wave (cw) optical field source the output from which is configured to pump the gain medium.

14. A self mode locking laser as claimed in claim 13 wherein the (cw) optical field source comprises a fibre coupled laser diode system.

15. A self mode locking laser as claimed in claim 1 wherein the resonator further comprises an astigmatism controller that provides a means for introducing astigmatism to the cavity mode at the gain medium.

16. A self mode locking laser as claimed in claim 15 wherein the resonator is configured such that the Kerr lensing layer acts to compensate for the astigmatism introduced to the cavity mode.

17. A self mode locking laser as claimed in claim 15 wherein the astigmatism controller comprises a mirror rotating means.

18. A self mode locking laser as claimed in claim 17 wherein the resonator is additionally folded by a fourth mirror, the fourth mirror being located along an optical path between the second and third mirrors, and wherein the mirror rotating means is employed to rotate the fourth mirror so as to vary an angle of incidence of a resonating field upon the fourth mirror.

19. A self mode locking laser as claimed in claim 1 wherein the laser provides an output field comprising ultra short pulses having a pulse width in the range of 100 ps to 100 fs.

20. A method of self mode locking a laser the method comprising:

- providing a resonator terminated by first and second mirrors and folded by a third mirror, the third mirror surmounted by a multilayer semiconductor gain medium including at least one quantum well layer and an optical Kerr lensing layer; and
- selecting a length of the resonator such that a round trip time of a cavity mode is substantially equal to an upper-state lifetime of one or more semiconductor carriers located within the gain medium to introduce a perturbation on an intensity of an output field of the laser causing the optical Kerr lensing layer to induce mode locking on the output field without the use of a saturable absorber.

21. A method of self mode locking a laser as claimed in claim 20 wherein the method further comprises locating an aperture stop having an aperture located therein within the resonator.

22. A method of self mode locking a laser as claimed in claim 21 wherein the aperture stop is located adjacent to the second mirror.

23. A method of self mode locking a laser as claimed in claim 20 wherein the method further comprises folding the resonator by providing a fourth mirror along an optical path between the second and third mirrors.

24. A method of self mode locking a laser as claimed in claim 23 wherein the method further comprises folding the resonator by providing a fifth mirror along an optical path between the second and fourth mirrors.

25. A method of self mode locking a laser as claimed in claim 24 wherein the method further comprises folding the resonator by providing a sixth mirror along an optical path between the second and fifth mirrors.

26. A method of self mode locking a laser as claimed in claim 20 wherein the method further comprises providing a continuous wave (cw) optical field configured to pump the gain medium.

27. A method of self mode locking a laser as claimed in claim 20 wherein the method further comprises introducing astigmatism to the cavity mode at the gain medium.

28. A method of self mode locking a laser as claimed in claim 27 wherein the method further comprises folding the resonator by providing a fourth mirror along an optical path between the second and third mirrors, wherein the astigmatism is introduced to the cavity mode by rotating the fourth mirror so as to increase the angle of incidence of a resonating field upon the fourth mirror.

29. A method of self mode locking a laser as claimed in claim 27 wherein the method further comprises configuring the resonator such that the Kerr lensing layer acts to compensate for the astigmatism introduced to the cavity mode.

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